

Ion-atom Collision Group(Annual Report)

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Ion-atom Collision Group

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Research Activities

(I) INNER-SHELL IONIZATION

(i) Heavy-charged particle impact

a. Ionization mechanism in high-energy region

Inner-shell ionizations by heavy-charged particle bombardment in low-energy region ($E/\lambda U < 1$) are mainly produced by the Coulomb interaction between the projectile and orbital electrons — close collisions. In high-energy region ($E/\lambda U > 1$), however, ionizations are also produced by the photoelectric effect of virtual photons induced by the projectile — distant collisions. By using the cyclotron of Tohoku University,¹⁾ we have measured the K-shell ionization cross sections of Au and Cu, L-shell ionization cross sections of Sn and Y, and M-shell ionization cross sections of Bi and Au over the proton-energy range 3–40 MeV. The results were separated into contributions from close and distant collisions,^{2–4)} and it was found that these contributions are expressed by

$$\sigma_{\text{dist.}}^i \approx \frac{1}{n} \sigma_{\text{close}}^i,$$

where $\sigma_{\text{total}}^i = \sigma_{\text{dist.}}^i + \sigma_{\text{close}}^i$ and n is the principal quantum number.

b. Alignment effect of ionized atoms

Cross sections of inner-shell ionization depend on the magnetic quantum number of the orbital electron to be ionized. Hence, the atoms are aligned as the result of ionization. We have measured the projectile-energy dependence of $L\alpha/L\beta$ intensity ratio, and have studied the effect of alignment.⁵⁾ The effect is, in general, easily found in low-projectile energy region.

c. Z_1^2 -dependence

The PWBA theory predicts the Z_1^2 -dependence of inner-shell ionization cross section; Z_1 is the projectile-charge number. In low-projectile energy region, however, deviation from this law has been observed because of the Coulomb deflection and the binding-energy effect. At high-projectile energy, deviation due to the polarization effect has been expected. Studies of this effect are now in progress on the K-shell ionizations of Al and Cu.

(ii) Heavy ion impact

a. Charge transfer

For a large value of projectile charge Z_1 , inner-shell ionizations are also caused by charge transfer of inner-shell electrons to the projectile. The cross section of this process is proportional to Z_1^5 , and this effect can therefore not be neglected in a heavy-ion impact. We have measured the K-shell ionization cross sections by N^{7+} -ions in comparison with those by α particles, and the charge-transfer process has been studied.⁶⁾ It was found the results are not so large as is predicted from the Brinckman-Krammers theory but the dependence of the cross section on projectile energy and on the target-atomic number is in good agreement with the theory.

b. Multiple ionization

Simultaneous multiple ionizations produced by heavy-ion impact have been calculated on the basis of probability theory. Some experimental results, however, are in disagreement with the calculation. Calculation in terms of the PWBA theory is now in progress.

(iii) Density effect in electron impact

The stopping power for ultrarelativistic electrons shows saturation beyond a certain value of incident electrons, and this phenomena has been explained by Fermi and has been called density effect. In inner-shell ionizations, however, this effect has not been observed contrary to the expectation. We have succeeded in observing experimentally this effect in the K-shell ionizations of light elements,^{7,8)} and have theoretically shown that this effect is not so remarkable as the prediction from the simple theory, since the frequency of the virtual photons is much higher in inner-shell ionizations than in the case of stopping power.

(II) OUTER-SHELL IONIZATION

Valence electrons connect atoms forming a molecule. So that, the state of valence electron can be studied by ionization of outer-shell electrons or indirectly by ionization of inner-shell electrons. A crystal spectrometer of energy resolution of a few eV with computer control is now under installation for studies of chemical effect. This apparatus can also be used for the study of multiple ionizations.

(III) BREMSSTRAHLUNG INDUCED BY ION-ATOM COLLISIONS

(i) Secondary electron bremsstrahlung (SEB)

Electrons ejected by inner-shell ionizations collide with a nucleus of other atom in the target and produce the bremsstrahlung. We have measured the production cross section of SEB over the incident proton-energy range 3-40 MeV, and it was found that the experimental results are smaller by one of magnitude than

the theoretical prediction. This disagreement was much improved by taking into account the effect of electron escape from the target and also by comparing the results for a thick target with those for a thin target.

(ii) Quasifree electron bremsstrahlung (QFEB)

Continuum x-ray spectra from targets of Be, C, and Al, bombarded with protons of 6–40 MeV, have been measured and besides SEB, another new component was clearly observed. This new component was well explained in terms of bremsstrahlung produced by the interaction between the projectile and inner-shell electrons. The Doppler shift of this spectrum definitely proves the production of these x rays in the projectile frame.

(iii) Internal secondary electron bremsstrahlung

In low-energy projectile impact, we have observed continuum x rays which can not be explained by SEB and have interpreted in terms of the bremsstrahlung induced by an electron in the field of atom from which the electron is ejected.⁹⁾ More precise calculations based on PWBA theory are in progress.

(IV) APPLICATIONS OF PARTICLE INDUCED X-RAY EMISSION (PIXE)

(i) PIXE with high-energy proton beams

It has been argued by Johansson et al. that the most favorable proton energy for PIXE is 1–3 MeV. We have measured the continuum background x rays for proton energies 3–12 MeV with our experimental setup in the cyclotron laboratory, where special care has been paid to reduce the background radiations. On the basis of the backgrounds actually measured and of the K- and L-x-ray production cross sections, the detection limit has been estimated and the merits of PIXE with 5–7 MeV protons have been found.

(ii) Element analysis of archeological samples

In an element analysis of archeological iron samples, characteristic x rays trace elements are masked by huge characteristic Fe-x-ray peaks. Hence, the effect of chemical treatment for eliminating Fe on the trace element in a sample are now being studied.

(iii) Monochromatic x-ray source

Since the characteristic x-ray production by heavy-charged particle impact has large cross sections, it is expected to use this process as an intense monochromatic x-ray source. We have already succeeded in getting sufficient schwärzung of x-ray film with K x rays from W and Ta targets bombarded with 6-MeV protons.

(V) CHARGED PARTICLE ACTIVATION ANALYSIS

(i) General formula for quantitative analysis

Activation analysis with charged particles has the highest sensitivity for some elements and has recently used for many purposes. Nevertheless, studies of

quantitative analysis with this method are very few. We have derived a quantitative formula, with an accuracy of $< 0.2\%$, in terms of average stopping power method for a sample where trace elements are uniformly distributed.¹⁰⁾ A formula for a sample with trace elements of non-uniform distribution is now being studied.

(ii) Measurements of nuclear-reaction data for activation analysis

- Activation analysis needs much data on nuclear reactions in order to choose the reaction for the analysis and to determine the projectile energy. Using the stack method, we have already measured the energy dependence of the reaction $^{16}\text{O}(^3\text{He}, p)^{18}\text{F}$, which is used for analysis of oxygen. Similar measurements on other reactions are being planned.

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